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Search for Large Extra Dimensions in the Monojet +  $\cancel{E}_T$  Channel at DØ

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We present a search for large extra dimensions (ED) in  $p\bar{p}$  collisions at a center-of-mass energy of 1.8 TeV using data collected by the DØ detector at the Fermilab Tevatron in 1994-1996. Data corresponding to  $78.8 \pm 3.9 \text{ pb}^{-1}$  are examined for events with large missing transverse energy, one high- $p_T$  jet, and no isolated muons. There is no excess observed beyond expectation from the standard model, and we place lower limits on the fundamental Planck scale of 1.0 TeV and 0.6 TeV for 2 and 7 ED, respectively.

The standard model (SM) of particle physics is a spectacular scientific achievement, with nearly every prediction confirmed to a high degree of precision. Nevertheless, the SM still has unresolved and unappealing characteristics, including the problem of a large hierarchy in the gauge forces, with gravity being a factor of  $10^{33} - 10^{38}$  weaker than the other three. A new framework for addressing the hierarchy problem was proposed recently by Arkani-Hamed, Dimopoulos, and Dvali [1], through the introduction of large compactified extra spatial dimensions in which only gravitons propagate. In the presence of  $n$  of these extra dimensions, the fundamental Planck scale in  $4 + n$  dimensions can be lowered to the TeV range, i.e., to a value comparable to the scale that characterizes the other three forces, thereby eliminating the puzzling hierarchy.

The radius ( $R$ ) of the compactified extra dimensions can be expressed as a function of a fundamental Planck scale,  $M_D \approx 1 \text{ TeV}$ , the number of extra dimensions  $n$ , and the usual Planck scale  $M_{\text{Pl}} = 1/\sqrt{G_N}$ . Assuming compactification on a torus, the relationship is [2]:

$$R = \frac{1}{\sqrt[n]{8\pi}M_D} (M_{\text{Pl}}/M_D)^{2/n}.$$

The value  $n = 1$  is ruled out by the  $1/r^2$  dependence of the gravitational force at large distances. The current limits from tests of gravity at short distances [3], as well as from stringent astrophysical and cosmological bounds [4], have significantly constrained the case of two extra dimensions. For  $n > 2$ , the constraints from direct gravitational measurements and cosmological observations are relatively weak. However, high-energy colliders can provide effective ways to test such models of large ED [5].

In the framework of large ED, at high energies, the strength of gravity in four dimensions is enhanced through a large number of graviton excitations, or Kaluza-Klein modes ( $G_{\text{KK}}$ ) [8]. This leads to new phenomena predicted for collisions at high energy [2, 9]: virtual graviton exchange and direct graviton emission. Virtual graviton exchange leads to anomalous difermion and diboson production, and searches for these effects have been pursued at the Tevatron [10], LEP [11], and HERA [12]. For real graviton emission, since the graviton escapes detection, the signature involves large missing transverse energy  $\cancel{E}_T$ , accompanying a single jet or a vector boson at large transverse momentum. LEP experiments [11] and the CDF collaboration [13] have recently set limits on  $M_D$  based on  $\gamma + G_{\text{KK}}$  production.

In this Letter, we report results of the first search for

large ED in the jet +  $\cancel{E}_T$  channel. The advantage of this channel is its relatively large cross section, with the trade-off of large background. Besides  $Z(\nu\bar{\nu}) + \text{jets}$ , which is the irreducible background, there are instrumental backgrounds from mismeasurement of, e.g., jet  $E_T$ , vertex position, undetected leptons, cosmic rays, etc. The data used for this search were collected in 1994 – 1996 by the DØ collaboration [14] at the Fermilab Tevatron, using proton-antiproton collisions at a center-of-mass energy of 1.8 TeV. This sample, representing an integrated luminosity of  $78.8 \pm 3.9 \text{ pb}^{-1}$ , was obtained using  $\cancel{E}_T$  triggers with thresholds between 35 and 50 GeV.

The DØ detector [14] consists of three major components: an inner detector for tracking charged particles, a uranium/liquid-argon calorimeter for measuring electromagnetic and hadronic showers, and a muon spectrometer consisting of magnetized iron toroids and three layers of drift tubes. Jets are measured with an energy resolution of approximately  $\sigma(E)/E = 0.8/\sqrt{E}$  ( $E$  in GeV).  $\cancel{E}_T$  is measured with a resolution of  $\sigma(\cancel{E}_T) = a + b \times S_T + c \times S_T^2$ , where  $S_T$  is the scalar sum of transverse energies in all calorimeter cells,  $a = 1.89 \pm 0.05 \text{ GeV}$ ,  $b = (6.7 \pm 0.7) \times 10^{-3}$ , and  $c = (9.9 \pm 2.1) \times 10^{-6} \text{ GeV}^{-1}$  [15].

After eliminating events of poor quality (e.g., containing hot cells in the calorimeter), events with one central (detector pseudorapidity  $|\eta_d| \leq 1.0$  [16]) high- $E_T$  jet ( $j_1$ ) and large  $\cancel{E}_T$ , with  $E_T(j_1) > 150 \text{ GeV}$  and  $\cancel{E}_T > 150 \text{ GeV}$ , were selected for further study. Since signal can contain initial or final-state radiation (ISR or FSR), additional jets can also be present in such interactions. To improve signal efficiency, we therefore allow additional jets in the event, but require the second jet ( $j_2$ ) to have  $E_T(j_2) < 50 \text{ GeV}$ , which reduces the background from dijet production, while retaining most of the signal containing ISR or FSR. To suppress  $W$  or  $Z$  production with a muon in the final state, as well as to reduce the background from cosmic rays, we reject events with isolated muons, that is, with  $\Delta\mathcal{R}(j_1, \mu) > 0.5$ , based mainly on information from the muon system (referred to at DØ as Isolated Muon Veto 1), and based on information from the calorimeter (Isolated Muon Veto 2), to suppress  $W$  or  $Z$  production with a muon in the final state as well as to reduce the background from cosmic rays. (The separation between objects is defined as  $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , where  $\eta$  is the pseudorapidity and  $\phi$  is the azimuthal angle.) Backgrounds with isolated electrons are expected to be small, and we therefore do not use any special criteria to suppress electrons. We also

TABLE I: Observed number of events passing each requirement in the data with  $E_T(j_1) > 150$  GeV,  $\cancel{E}_T > 150$  GeV, and  $E_T(j_2) < 50$  GeV.

Criterion	Number of Events
Event Quality	301,325
Isolated Muon Veto 1	296,742
Leading-jet, $\cancel{E}_T$ and Second-jet Requirement	141
$\Delta\phi(j_2, \cancel{E}_T)$	129
Cosmic Ray Rejection	69
Primary Vertex Confirmation	39
Isolated Muon Veto 2	38

require  $\Delta\phi(j_2, \cancel{E}_T) > 15^\circ$ , to reduce the background from mismeasured jets in multijet (“QCD”) events. An additional source of background is from hard bremsstrahlung of cosmic-ray muons that pass through the DØ calorimeter. For any showers induced by photons radiated in the hadronic layers of the calorimeter, the resulting “jets” usually contain only a handful of cells with significant energy deposition, and such jets therefore fail our quality criteria. However, for bremsstrahlung that occurs in the EM section of the calorimeter, the shower is usually reconstructed as an EM object, and not as a jet. Thus, most of the background arises from showers that originate near the regions of confusion at the interface of the EM and hadronic calorimeters. To reduce this background, we remove events with such “jets”, as well as events that contain “tracks” of minimum energy deposition, which are typical of muons observed in the finely segmented DØ calorimeters. Jet “pointing”, based on tracking information in the leading jet ( $j_1$ ), is used to confirm the longitudinal position of the primary vertex by requiring that  $\Delta z(j_1\text{-vertex}, \text{primary-vertex}) \leq 10$  cm. This suppresses background from cosmic rays as well as from events with incorrectly reconstructed primary vertexes. The requirements on  $\eta_d$  of the leading jet and on the event primary vertex confirmation are chosen to maximize the significance of signal relative to background. A total of 38 events remain in the data sample after applying all selections, as shown in Table I.

The PYTHIA Monte Carlo (MC) generator [17], with implementation of the ED signal via Ref. [18], including the parton-level subprocesses  $qg \rightarrow qG_{KK}$ ,  $q\bar{q} \rightarrow gG_{KK}$ , and  $gg \rightarrow gG_{KK}$ , is used to generate signal events. This is followed by processing through DØ fast-detector simulation QSIM routines[19]. The signal is simulated for  $n = 2$  to  $n = 7$  extra dimensions, with  $M_D$  ranging from 600 GeV to 1400 GeV in 200 GeV steps. The acceptance for signal varies from about 5% to 8%, depending on the values of  $n$  and  $M_D$ . The 13% contribution to the uncertainty on the overall acceptance is due to the limited size of the MC samples, and is of the same order as the contributions from the jet-energy scale [20] (5–12%) and the choice of parton distribution functions (PDFs) (3–5%). (The CTEQ3M set of parton distribution functions

TABLE II: The expected and observed number of events in the final jet +  $\cancel{E}_T$  sample.

Background	$N$
$Z(\nu\nu) + \text{jets}$	$21.0 \pm 5.1$
$Z(ee) + \text{jets}$	$< 0.01$
$Z(\mu\mu) + \text{jets}$	$0.01 \pm 0.01$
$Z(\tau\tau) (+ \text{jets})$	$< 0.09$
$W(e\nu) + \text{jets}$	$3.1 \pm 0.7$
$W(\mu\nu) + \text{jets}$	$0.8 \pm 0.3$
$W(\tau\nu) (+ \text{jets})$	$5.2 \pm 2.3$
QCD and cosmic	$7.8 \pm 7.1$
Total background	$38.0 \pm 9.6$
Data	38

(PDFs) [21] was used as a default choice in the analysis.)

The SM background from  $W$  and  $Z$ -boson production is also modeled by PYTHIA, followed by QSIM detector simulation. We normalize the  $W$  and  $Z$  production cross sections to the published DØ measurements in the electron channel [22]. The sources of background are detailed in Table II. With our event selection, the contribution from backgrounds other than  $Z(\nu\bar{\nu}) + \text{jets}$  is small, and the background from all  $W$  and  $Z$  sources is estimated to be  $30.2 \pm 6.4$  events. The dominant uncertainty on the estimate of  $Z(\nu\bar{\nu}) + \text{jets}$  is from the uncertainty of the jet-energy scale. The residual background from mismeasured multijet events and cosmic muons is estimated from data, using the uncorrelated  $\Delta z$  and  $\Delta\phi$  variables described above: we define four data samples, depending on whether the events pass or fail the above criteria; we then normalize the events that fail event vertex confirmation to the candidate sample, using the ratio of the number of events in the two data samples with  $\Delta\phi(j_2, \cancel{E}_T) \leq 15^\circ$ ; the background from QCD and cosmic rays in the candidate sample is thereby estimated as:

$$N_{\text{QCD} + \text{cosmics}} = N_{\Delta\phi > 15^\circ}^{\Delta z > 10} \times N_{\Delta\phi \leq 15^\circ}^{\Delta z \leq 10} / N_{\Delta\phi \leq 15^\circ}^{\Delta z > 10}.$$

This yields  $7.8 \pm 7.1$  events. The uncertainty is due primarily to the low statistics of the data samples. The total background estimate is  $38 \pm 10$  events. As shown in Fig. 1(a), the  $\cancel{E}_T$  distribution in the data is consistent with that expected from background. Examination of the event with  $\cancel{E}_T$  near 450 GeV reveals that the energy deposited by the jet is concentrated in only three calorimeter layers, typical of Bremsstrahlung from a cosmic muon, rather than from a true jet. Nevertheless, the event is kept in the candidate sample, as it passes all *a priori* selection criteria. From extrapolation, we expect about  $0.2 \pm 0.2$  background events for  $\cancel{E}_T > 300$  GeV.

As a cross check of our background estimate, we define a data sample with less stringent requirements, while maintaining roughly the same  $E_T(j_1)/E_T(j_2)$  ratio:  $E_T(j_1) > 115$  GeV,  $\cancel{E}_T > 115$  GeV, and  $E_T(j_2) < 40$  GeV. We estimate the background in this sample using the same techniques as described above. This yields an

expectation of  $105 \pm 16$   $W/Z + \text{jets}$  events and  $16 \pm 9$  QCD and cosmic ray events, consistent with the 127 events observed in this data sample. The  $\cancel{E}_T$  distributions for this sample and for the expected background are shown in Fig. 1(b).

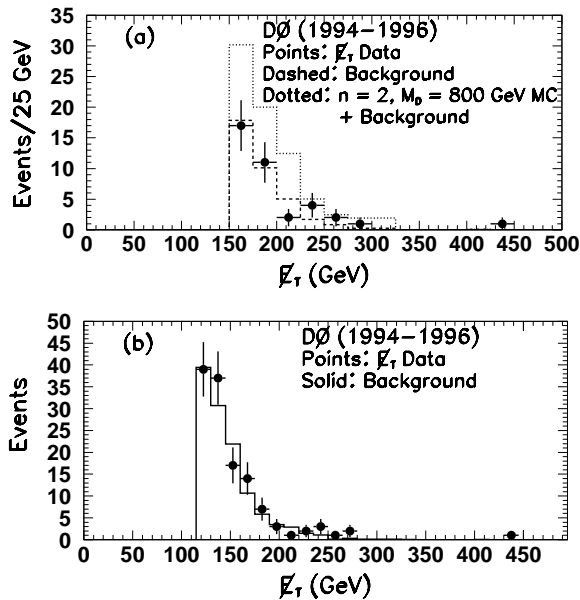


FIG. 1: (a) Comparison of data (points with error bars) with expected background (dashed histogram), and the sum of background and signal for  $n = 2$ ,  $M_D = 800$  GeV (dotted histogram), as a function of  $\cancel{E}_T$ , for  $E_T(j_1) > 150$  GeV,  $\cancel{E}_T > 150$  GeV, and  $E_T(j_2) < 50$  GeV; and (b) comparison of  $\cancel{E}_T$  for data with  $E_T(j_1) > 115$  GeV,  $\cancel{E}_T > 115$  GeV, and  $E_T(j_2) < 40$  GeV with expected background.

In the absence of evidence for large ED, we calculate upper limits on the cross section for such processes. These limits can be interpreted as lower bounds on the fundamental Planck scale  $M_D$  for different integer values of  $n$ , as listed in Table III. Using a Bayesian approach [23], we set limits on  $n$  and  $M_D$  using the leading-order cross sections, as well as approximate estimates of next-to-leading-order (NLO) corrections via a constant  $K$ -factor of 1.34, typical of processes at the Tevatron energies, e.g., Drell-Yan [24] or direct photon production. As there are no NLO calculations of direct graviton emission to date, the limits with the  $K$ -factor should be regarded with caution, as purely a measure of sensitivity to the (unknown) NLO effects. The exclusion contours at 95% confidence, and a comparison with limits from LEP and CDF for the single-photon channel [11, 13], are shown in Fig. 2. While the DØ limits are worse than those from LEP at low values of  $n$ , the sensitivity of the monojet search exceeds the LEP sensitivity at large  $n$ , due to the higher center-of-mass energy at the Tevatron. The limits correspond to compactification radii ranging from  $R < 0.6$  mm ( $n = 2$ ) to  $R < 9$  fm ( $n = 7$ ), without correcting for the  $K$ -factor, and  $R < 0.5$  mm ( $n = 2$ ) to  $R < 9$  fm ( $n = 7$ ) with approximate NLO effects taken into account. For all  $n$ , the sensitivity in the single-

photon channel at the Tevatron is not as high as in the monojet channel, as the comparison with the CDF limits in Fig. 2 demonstrates.

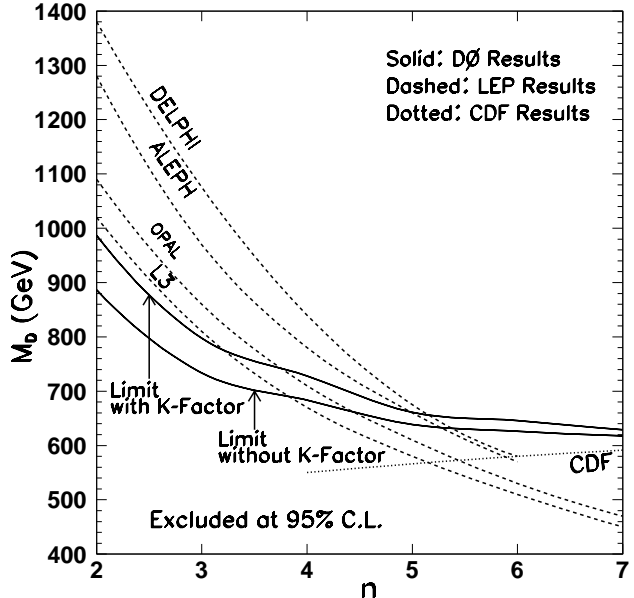


FIG. 2: The 95% C.L. exclusion contours on the fundamental Planck scale ( $M_D$ ) and number of extra dimensions ( $n$ ) for monojet production at DØ (solid lines). The dashed curves correspond to limits from LEP, and the dotted curve is the limit from CDF, both for  $\gamma + G_{KK}$  production.

TABLE III: 95% C.L. lower limits on  $M_D$ .

$n$	2	3	4	5	6	7
$M_D$ limit without $K$ -factor scaling (TeV)	0.89	0.73	0.68	0.64	0.63	0.62
$M_D$ limit with $K$ -factor scaling (TeV)	0.99	0.80	0.73	0.66	0.65	0.63

In summary, we have performed the first search for large extra dimensions in the monojet channel. No evidence for large extra dimensions is observed. We set 95% confidence-level lower limits on the fundamental Planck scale between 0.6 and 1.0 TeV, depending on the number of extra dimensions. Our limits are complementary to those obtained at LEP in the single photon channel, and are most restrictive to date for  $n > 5$ .

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